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Ambient Coarse Particulate Matter and Hospital Admissions in the Medicare Cohort Air Pollution Study, 1999-2010

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Abstract

Background: In recent years a number of studies have examined the short-term association between coarse particulate matter ($PM_{10-2.5}$) and mortality and morbidity outcomes. These studies, however, have produced inconsistent conclusions.

Objectives: We estimated both the national- and regional-level associations between $PM_{10-2.5}$ and emergency hospitalizations for both cardiovascular and respiratory disease among Medicare enrollees over 65 years of age during the 12-year period 1999 through 2010.

Methods: Using air pollution data obtained from the U.S. Environmental Protection Agency air quality monitoring network and daily emergency hospitalizations for 110 large urban U.S. counties assembled from the Medicare Cohort Air Pollution Study (MCAPS), we estimated the association between short-term exposure to $PM_{10-2.5}$ and hospitalizations using a two-stage Bayesian hierarchical model and Poisson log-linear regression models.

Results: A 10 $\mu g/m^3$ increase in $PM_{10-2.5}$ was associated with a significant increase in same-day cardiovascular hospitalizations (0.69%; 95% posterior interval (PI): 0.45, 0.92). After adjusting for $PM_{2.5}$ this association remained significant (0.63%; 95% PI: 0.38, 0.88). A 10 $\mu g/m^3$ increase in $PM_{10-2.5}$ was not associated with a significant increase in respiratory related hospitalizations.

Conclusions: We found statistically significant evidence that daily variation in $PM_{10-2.5}$ is associated with emergency hospitalizations for cardiovascular diseases amongst Medicare enrollees aged 65 years and above. This association was robust to adjustment for concentrations of $PM_{2.5}$.

Introduction

Particle size is known to influence the deposition of airborne particulate matter (PM) within the respiratory tract. Currently, both particles which are less than 10 µm in aerodynamic diameter (PM_{10}) and those which are less than 2.5 µm in aerodynamic diameter (fine, $PM_{2.5}$) are considered harmful to human health by the World Health Organization (WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide 2005). Governing bodies around the world, including the U.S. Environmental Protection Agency (EPA), currently monitor and regulate particulate matter at these metrics. However, it is difficult to disentangle the health effects associated with PM_{10} from those associated with $PM_{2.5}$ because PM_{10} measurements largely consist of the finer $PM_{2.5}$ particles (Brunekreef and Forsberg 2005).

As a result, a number of studies have estimated the health effects associated with coarse PM which includes particles between 2.5 and 10 µm in aerodynamic diameter ($PM_{10\text{-}2.5}$). Coarse PM is also referred to as coarse thoracic PM because the inhaled particles are deposited in the lower respiratory tract. $PM_{10\text{-}2.5}$ particles are primarily crustal in nature (Chang et al. 2011), while $PM_{2.5}$ particles are primarily generated by combustion processes (EPA 2009). However, the evidence evaluated from such studies has provided inconsistent conclusions and as such led the 2009 Integrated Science Assessment from the EPA to determine the causal relationship between health outcomes and $PM_{10\text{-}2.5}$ as "suggestive" (EPA 2009). As of January 2013, the National Ambient Air Quality Standards (NAAQS) did not include a standard for $PM_{10\text{-}2.5}$ and instead retained the current standards for PM_{10} as a means of controlling for $PM_{10\text{-}2.5}$.

A large national study of $PM_{10\text{-}2.5}$ and hospitalizations for cardiovascular and respiratory diseases in the Medicare population was conducted in 2008 (Peng et al. 2008). That study found that daily changes in $PM_{10\text{-}2.5}$ were positively correlated with daily cardiovascular hospitalizations but that this association was not statistically significant once it was adjusted for concurrent day $PM_{2.5}$ concentrations. In this study no statistically significant association was found between $PM_{10-2.5}$ and respiratory hospitalizations. A key limitation of Peng et al. 2008 was the limited sample size (and hence power), which only included data from 1999 to 2005. Because estimating $PM_{10-2.5}$ concentrations requires measurements of PM_{10}, which is typically measured on a less frequent 1-in-6 day schedule, data were not as abundant for that study as they were for previous national studies of $PM_{2.5}$ alone (e.g. Bell et al. 2008 and Dominici et al. 2006).

The lack of clear national evidence on the health effects of $PM_{10-2.5}$ and the continuing lack of a national ambient air quality standard specifically for this size fraction motivates the current study. From Medicare, a national social insurance program which guarantees access to health care for American citizens aged 65 and above, we assembled a national database of cause-specific emergency hospitalizations amongst people in this age category. These data were linked with corresponding national databases of air pollution concentrations and weather information for 110 large urban communities within the U.S. spanning the 12 year period 1999 to 2010, nearly double the sample size of the Peng et al. 2008 study, which also examined this population. Using these national databases we conducted a multi-site time series study to investigate the short-term association between $PM_{10-2.5}$ and daily hospitalization for cardiovascular and respiratory diseases in an elderly population.

Materials and Methods

Data

The data here represent an extension of the Medicare Cohort Air Pollution Study (MCAPS) described previously (Dominici et al. 2006; Peng et al. 2008). For the study period January 1, 1999 through December 31, 2010 there are 110 U.S. counties which were eligible for inclusion in this study. Counties were eligible for inclusion if they had greater than 20,000 Medicare enrollees aged 65 years and above in the year 2000, had PM_{10} and $PM_{2.5}$ recorded at collocated monitors for at least 200 days of the study period (January 1, 1999 through December 31, 2010), and with at least 90% of the measured PM_{10} concentrations being greater in value than the collocated $PM_{2.5}$ concentrations to ensure positive values of $PM_{10-2.5}$, where $PM_{10-2.5}$ is estimated by subtracting $PM_{2.5}$ from PM_{10}. In addition, the overdispersed Poisson log-linear model used to estimate county-level associations in the first stage of our analysis (as described in detail below) had to converge within a prespecified number of iterations when run using the data from a potentially eligible county. A total of 110 counties that met these criteria were included in our analysis (Figure 1). As in Dominici et al. 2006 we classified counties into western and eastern regions according to their location relative to -100.00° longitude (n = 29 and 81 counties, respectively).

The health outcome of interest is the daily number of emergency hospital admissions for cardiovascular and respiratory diseases that can be derived from the billings claims of Medicare enrollees from the National Claims History Files. Medicare is a national social insurance program which guarantees access to health insurance for American citizens aged 65 years and above. As of 2012, 42.1 million people, approximately 94% of the American population in this age category, were enrolled in the Medicare program (Board of the Trustees of the Federal Hospital Insurance and Federal Supplementary Medical Insurance Trust Funds 2013). The billings claim for each individual includes demographic and county of residence information in addition to the medical record. It is therefore possible to know the age of each claimant, which county they reside in, the date of their admission to the hospital and their primary disease classification, which is given in accordance with the International Classification of Diseases, Ninth Revision (ICD-9).

We consider separately the broad outcomes of cardiovascular and respiratory disease, where the primary diagnosis at the time of admission to the hospital was used as the basis for inclusion into either category. We consider the same individual diagnoses as Peng et al. 2008, all of which have previously been associated with particulate matter (Bell et al. 2008; Burnett et al. 1999; Lippmann et al. 2000). Specifically, we evaluated hospitalization for a primary diagnosis of cardiovascular outcomes (as a group and individually), including cerebrovascular events (CVD, 430-438), heart failure (HF, 428), heart rhythm disturbances (HRD, 426-427), ischemic heart disease (IHD, 410-414, 429) or peripheral vascular disease (PVD, 440-448). We also evaluated hospitalization for two respiratory outcomes (combined and individually): chronic obstructive pulmonary disease (COPD, 490-492) or respiratory tract infection (RTI, 464-466, 480-487). For each county a daily time series of the hospitalization rates were constructed for both the individual diagnoses and the combined cardiovascular and respiratory outcomes. For the time period under consideration there were a total of 6.37 million cardiovascular and 2.51 million respiratory emergency hospitalizations over the 110 counties.

The U.S. Environmental Protection Agency (EPA) employs a population orientated air quality monitoring network which utilizes gravimetric methods to analyze atmospheric pollutants. Both $PM_{2.5}$ and PM_{10} are currently monitored by this network (http://1.usa.gov/1oJDcyz). Therefore, we derived an indicator of $PM_{10-2.5}$ by subtracting the daily measured $PM_{2.5}$ concentrations from the same day PM_{10} concentrations at locations with collocated monitors, as routinely performed by the U.S. EPA (Vanderpool et al. (2004)) and commonly used in epidemiological studies. For counties with more than a single pair of collocated monitors we applied a 10% trimmed mean

(Samet et al. 2000) to obtain a single estimate of $PM_{10-2.5}$ for each day of the study and protect against outliers. If there were fewer than 10 collocated monitors then we instead dropped the minimum and maximum values for that day; if only 2 estimates were available then the average was used. This method has been used in numerous previous air pollution studies (e.g. Peng et al. 2008 and Dominici et al. 2006). Additionally, we obtained daily temperature and dew-point temperature data for each county from the National Climatic Data Center (NCDC 2014), as both are potential confounders of the association between health outcomes and air pollution exposures.

Analyses

To estimate both regional (eastern versus western U.S.) and national associations between $PM_{10-2.5}$ and county-level hospitalization rates, a two-stage Bayesian hierarchical model was used. Adjustments were made for $PM_{2.5}$, weather, seasonal and long-term trends, as described below. In addition to the single day exposure lags of 0, 1 and 2 days, which were originally considered by Peng et al. 2008, we also looked at an exposure lag of 3 days. We included this additional lag as a number of recent studies have found a significant association between $PM_{10-2.5}$ and a health outcome at this longer 3 day lag period (Tecer et al. 2008) or at an average exposure level which includes days 0 to 3 (Bell et al. 2008; Qiu et al. 2012; Qiu et al. 2013). Due to the small subset of counties with daily data we did not however include a 3 day moving average lag.

In the first stage, we stratified the time series by age creating two categories: one for those Medicare enrollees aged between 65 and 74 years of age and one for those aged 75 years and above. We used an overdispersed Poisson log-linear model to estimate county-level associations between $PM_{10-2.5}$ and hospitalizations. This model included: an offset of the natural logarithm of the number of people at risk on a given day in that county, taken to be the total number of

Medicare enrollees for that county on that day; a separate intercept for each age category, to account for differing baseline hospitalizations rates in each of the age categories (65-74 years of age and 75 years and above); an indicator for the day of the week; an indicator for those aged 75 years and above; smooth functions of the current day's temperature and the mean of the previous 3 day's temperature, both of which used 6 degrees of freedom; smooth functions of the current day's dew point temperature and the mean of the previous 3 day's dew point temperature, both of which used 3 degrees of freedom; a smooth function of calendar time, with 8 degrees of freedom per year for cardiovascular admissions and 12 per year for respiratory admissions (respiratory admissions are more strongly seasonal than cardiovascular admissions); a smooth function of time interacting with the indicator for age to capture the varying long-term time trends, with 1 degree of freedom per year, and; the daily $PM_{10-2.5}$ concentrations at the given lag. Each of the smooth functions was included as a natural cubic spline. The degrees of freedom per year for the smooth function of time were chosen so that longer-term and seasonal fluctuations in $PM_{10-2.5}$ and hospitalizations were removed, leaving only shorter-term fluctuations for estimating health effects. Degrees of freedom for the temperature and dew-point temperature smooth functions were chosen to accommodate non-linear relationships between these factors and the health outcomes (Curriero et al. 2002). Additionally, a second model was also fit which included, in addition to the variables listed above, $PM_{2.5}$ concentrations. Simultaneously including both $PM_{10-2.5}$ and $PM_{2.5}$ at the same lag allows us to adjust for the potential effect of $PM_{2.5}$. This model was implemented in the statistical software R using the glm function which uses only complete cases in the analysis.

At the second stage, we estimated the national and regional level associations between $PM_{10-2.5}$ and hospital admissions using Bayesian hierarchical models within the tlnise package (Everson and Morris 2000). This allows us to combine the relative risk estimates across counties while accounting for within-county statistical error and between-county variability of the true relative risks. The county-specific relative risks over all 110 counties were combined to produce a national level estimate. Similarly, regional estimates for the western and eastern U.S. were produced by combining the county-specific relative risks for the 29 counties which lie to west and the 81 counties which lie to the east.

Statistical significance was assessed by the 95% posterior intervals excluding the value of zero.

Sensitivity Analysis

We assessed the sensitivity of the same day national estimates for the cardiovascular and respiratory hospitalization rates with respect to the degrees of freedom which were used in the smooth functions of time, temperature and dew-point temperature. For both calendar time and temperature we considered a range of degrees of freedom from 2 to 20 and for dew point temperature we considered a range from 1 to 10. The different choices for the degrees of freedom for each smooth function were considered independently of the other smooth functions.

Results

Regionally, the daily admission rates were higher in the eastern U.S. as compared to the west for both cardiovascular and respiratory diseases (Table 1).

During the study period, median $PM_{10-2.5}$ concentrations were lower for counties in the east compared with counties in the west, while the opposite pattern was observed for $PM_{2.5}$ (Figure 1 and Table 2). The schedule for measuring PM_{10} and $PM_{2.5}$ in each county is not always daily and in some counties it may be as infrequent as once in every six days for PM_{10} and once in every three days for $PM_{2.5}$. Therefore, there are only a limited number of days for which $PM_{10-2.5}$ can be estimated. Over all counties, the median number of days for which it was possible to estimate $PM_{10-2.5}$ was 681 with 25th and 75th percentiles of 515 and 1188, respectively. Both temperature and dew-point temperature are higher in the eastern U.S (Table 2).

The results of both the national (Figures 2 and 4) and regional (Figure 3) level associations are presented as the percentage change in the number of emergency hospitalizations for a 10 $\mu g/m^3$ increase in coarse particulate matter, with associated 95% posterior intervals (PIs). Results are shown for lags 0, 1, 2 and 3 days for both the single pollutant (only $PM_{10-2.5}$ is included) and two pollutant ($PM_{10-2.5}$ and $PM_{2.5}$ are jointly included) models.

Under both the single pollutant and two-pollutant models we found that a 10 $\mu g/m^3$ increase in $PM_{10-2.5}$ was associated with a statistically significant increase in cardiovascular hospitalizations on the same day as exposure, with increases of 0.69% (95% PI: 0.45, 0.92) and 0.63% (95% PI: 0.38, 0.88) respectively under each model (Figure 2). Exposure at a lag of 1, 2 or 3 days was not significantly associated with the number of cardiovascular admissions under either model. Respiratory hospitalizations were not significantly associated with $PM_{10-2.5}$ on the same day or any of the previous 3 days of exposure under either the single pollutant or two-pollutant models (Figure 2). After adjusting for $PM_{10-2.5}$, a 10 $\mu g/m^3$ increase in $PM_{2.5}$ was associated with a significant increase in respiratory hospitalizations on the same day (0.67%; 95% PI: 0.14, 1.21), while the association with cardiovascular admissions was not significant (0.31%; 95% PI: -0.02, 0.64).

A 10 $\mu g/m^3$ increase in $PM_{10-2.5}$ was positively associated with cardiovascular admissions on the same day in both eastern (0.84%; 95% PI: 0.51, 1.17) and western counties (0.44%; 95% PI: 0.04, 0.85) (Figure 3). After adjusting for $PM_{2.5}$ the association remained statistically significant for the eastern (0.74%; 95% PI: 0.38, 1.10) but not the western region (0.41%; 95% PI: -0.03, 0.85). Under both the single and two-pollutant models, exposure at a lag of 1, 2 or 3 days was not associated with a significant change in cardiovascular admissions in the eastern U.S. In the west $PM_{10-2.5}$ was negatively associated with both cardiovascular and respiratory admissions at these lags under both models. At an exposure lag of 2 days this negative association was significant for cardiovascular admissions (single pollutant model, -0.52%; 95% PI: -0.97, -0.08 and two-pollutant model, -0.54%, 95% PI: -1.00, -0.08). A 10 $\mu g/m^3$ increase in $PM_{10-2.5}$ was not significantly associated with respiratory admissions in either the eastern or western U.S. at any exposure lag. These estimates and associated posterior intervals are less precise, as demonstrated by the wider intervals, than those for the cardiovascular outcome due to the small number of respiratory admissions (Figure 3).

When examining the sub-categories of cardiovascular admissions, a 10 $\mu g/m^3$ increase in $PM_{10-2.5}$ was associated with a significant increase in cerebrovascular disease, 0.72% (95% PI: 0.22, 1.21); 0.74% (95% PI: 0.22, 1.27), heart rhythm disturbances, 0.94% (95% PI: 0.40, 1.48); 0.82% (95% PI: 0.26, 1.38), and ischemic heart disease, 0.74% (95% PI: 0.29, 1.20); 0.76% (95% PI: 0.27, 1.25), admissions on the same day (Figure 4) under both the single and two-pollutant models respectively. This increase in $PM_{10-2.5}$ was also associated with a non-significant rise in same day heart failure (0.40%; 95% PI: -0.06, 0.87) and peripheral vascular disease (0.89%; 95% PI: -0.27, 2.05) admissions under the single pollutant model. Compared to heart failure, peripheral vascular disease was more strongly associated with same day $PM_{10-2.5}$ however, this estimated association was relatively imprecise due to the small number of admissions for this disease. A 10 $\mu g/m^3$ increase in $PM_{10-2.5}$ was not significantly associated with hospital admissions due to chronic obstructive pulmonary disease (0.31%; 95% PI: -0.39, 1.01;

0.19%; 95% PI: -0.54, 0.92) or respiratory tract infections (0.07%; 95% PI: -0.46, 0.61; -0.02; 95% PI: -0.59, 0.55), under either the single or two-pollutant models respectively. Exposure on previous days (lag 1, 2, or 3) was also not associated with significant change in hospital admissions for any of the individual subcategories under either model.

We independently assessed the sensitivity of the same day national average estimates with respect to the degrees of freedom used in the smooth functions of time, temperature and dew-point temperature under the single pollutant model. From Figure 5 we can see that neither the cardiovascular nor respiratory hospitalization estimates showed substantial sensitivity to the choice of degrees of freedom for either the smooth functions of temperature or dew-point temperature. The estimates are slightly more sensitive to the choice of degrees of freedom per year for the smooth function of time, particularly those relating to the respiratory admissions. However, given the very small number of degrees of freedom which we considered and the increasing width of the 95% posterior intervals this small amount sensitivity is to be expected.

Discussion

Using data on Medicare enrollees aged 65 years and older for the 12-year period, January 1, 1999 to December 31, 2010, we found same-day exposure to $PM_{10-2.5}$ was associated with increased cardiovascular hospitalizations, even after adjusting for $PM_{2.5}$. We did not find evidence that $PM_{10-2.5}$ was associated with respiratory hospitalizations, with or without adjustment for $PM_{2.5}$.

Although previous studies have also found positive associations between cardiovascular hospitalizations and short-term exposure to $PM_{10-2.5}$ (Brunekreef and Forsberg 2005; Stafoggia et al. 2013; Peng et al. 2008; Qiu et al. 2013), only one previous study examined these associations in a multi city U.S. study (Peng et al. 2008). Using a Medicare hospitalizations dataset from 1999 to 2005, Peng et al. 2008 conducted a national study of 108 U.S. counties and found that a 10 μg/m^3 increase in $PM_{10\text{-}2.5}$ was associated with a 0.36% (95% PI: 0.05, 0.68) increase in cardiovascular admissions, but this association was not statistically significant after controlling for $PM_{2.5}$, 0.25% (95% PI: -0.11, 0.60). We expanded the analysis of Peng et al. 2008 to include data for an additional 5 years (1999 to 2010) and found that a 10 μg/m^3 increase in $PM_{10\text{-}2.5}$ was associated with an statistically significant increase in cardiovascular hospitalizations, both without (0.69%; 95% PI: 0.45, 0.92) and with adjustment for $PM_{2.5}$ (0.63%; 95% PI: 0.38, 0.88). Despite using almost identical data and methods to those of Peng et al. 2008 our national estimates are greater in magnitude and in the case of cardiovascular admissions, robust to adjustment for $PM_{2.5}$. Possible explanations for this may include differences in the chemical composition of $PM_{10\text{-}2.5}$ or differences in the overall health of the U.S. population from 1999 to 2010.

A 2005 literature review found evidence of associations between $PM_{10\text{-}2.5}$ and increased respiratory morbidity (Brunekreef and Forsberg 2005), though the evidence from studies conducted since 2005 is more mixed (Peng et al. 2008; Stafoggia et al. 2013; Host et al. 2008 Qiu et al. 2012; Malig et al. 2013). Only one recent U.S. study found an association between $PM_{10\text{-}2.5}$ and increased respiratory morbidity (Malig et al. 2013), however, 45% of the total cases included in this study were children under 18. Additionally, this study focused on respiratory emergency department visits and might estimate a different underlying association between $PM_{10\text{-}2.5}$ and respiratory morbidity than studies which focused on emergency respiratory hospitalizations. A study of 6 French cities found $PM_{10\text{-}2.5}$ was associated with increased respiratory hospitalizations in children under the age of 14, but not in adults over 65 (Host et al.

2008). As in another study of the U.S. Medicare population over 65 (Peng et al. 2008), we did not find short-term exposure to $PM_{10-2.5}$ was significantly associated with respiratory hospitalizations.

Previous studies have also found short-term exposure to $PM_{10-2.5}$ to be associated with increased mortality (Zanobetti and Schwartz 2009; Atkinson et al. 2010; Lopez-Villarrubia et al. 2012; Malig and Ostro 2009; Brunekreef and Forsberg 2005). Although the magnitude of these mortality effect estimates were very varied, the largest U.S. study of $PM_{10-2.5}$ and mortality estimated effects similar in magnitude to those estimated in our study for cardiovascular hospitalizations (Zanobetti and Schwartz 2009).

In the study presented here, we found significant associations between $PM_{10-2.5}$ and sub-categories of cardiovascular disease hospitalizations, including cerebrovascular disease, heart rhythm disturbances and ischemic heart disease. Heart failure and peripheral vascular disease, which are also sub-categories of cardiovascular admissions, were not significantly associated with $PM_{10-2.5}$. Other single city studies have not found statistically significant associations between $PM_{10-2.5}$ and hospitalizations due to cerebrovascular disease (Bell et al. 2008; Qiu et al. 2013; Halonen et al. 2009), heart failure (Lippmann et al. 2000), or heart rhythm disturbances (Halonen et al. 2009; Lippmann et al. 2000; Burnett et al. 1999), though no national or regional studies have previously been conducted. Single city studies have found associations with ischemic heart disease (Bell et al. 2008; Host et al. 2008; Qiu et al. 2013; Lippmann et al. 2000; Burnett et al. 1999) and peripheral vascular disease (Burnett et al. 1999) hospitalizations. In our national level study, we did not find evidence that $PM_{10-2.5}$ was associated with hospitalizations due to COPD or respiratory tract infections, though some previous studies of single cities have found $PM_{10-2.5}$ to be associated with hospitalizations due to COPD (Qiu et al. 2012; Burnett et al.

1999; Chen et al. 2004), combined asthma and COPD (Halonen et al. 2009), and respiratory infections (Burnett et al. 1999; Lippmann et al. 2000).

In a regional analysis, we found that $PM_{10-2.5}$ was more strongly associated with cardiovascular hospitalizations in the eastern U.S. than in the west. The regional differences in estimated health effects of $PM_{10-2.5}$ may be explained by regional differences in the chemical composition $PM_{10-2.5}$, which varies with the sources of $PM_{10-2.5}$ which include sea spray, road dust, erosion, and bioaerosols (EPA 2009). While the concentration of $PM_{10-2.5}$ was higher in the west compared with the east, the chemical constituents present in $PM_{10-2.5}$ may be more toxic in the east. Because the chemical composition of $PM_{10-2.5}$ is not measured at the national scale in the U.S., we cannot determine whether regional differences in estimated health effects of $PM_{10-2.5}$ are attributable to chemical composition in this study. Regional differences in estimated health effects may also be driven by differences in personal exposure attributable to differences in air conditioning use or time spent outdoors. We estimated some negative associations between cardiovascular admissions and $PM_{10-2.5}$ in the west at longer exposure lags. One possible explanation for such an observation is the presence of a short-term displacement of hospitalizations over the course of a few days, similar to what has occasionally been observed with mortality outcomes (Dominici et al. 2003).

Some previous studies outside the U.S. have found effect estimates for $PM_{10-2.5}$ which were similar in magnitude to estimated effects for $PM_{2.5}$ (Host et al. 2008; Bell et al. 2008; Halonen et al. 2009; Stafoggia et al. 2013). While we did not estimate associations for $PM_{2.5}$ in this study, previous national-level studies of $PM_{2.5}$ have estimated larger effect magnitudes for cardiovascular hospitalizations than we found in this study of $PM_{10-2.5}$ (Dominici et al. 2006; Peng et al. 2008; Zanobetti et al. 2009). In contrast with previous studies of the health effects of

$PM_{10-2.5}$ (Peng et al. 2008; Qiu et al. 2012; Qiu et al. 2013; Stafoggia et al. 2013), we found that the estimated associations between $PM_{10-2.5}$ and hospitalizations were only slightly decreased after adjusting for $PM_{2.5}$.

Limitations

In the U.S., there is no national monitoring system for $PM_{10-2.5}$ and most studies use the indirect method of taking the difference between PM_{10} and $PM_{2.5}$ to estimate $PM_{10-2.5}$ concentrations. This indirect approach leads to more measurement error than if we monitored $PM_{10-2.5}$ directly because of the measurement error present in the observations of both PM_{10} and $PM_{2.5}$. We did not have daily measurements of $PM_{10-2.5}$ in every county because of the monitoring schedules for $PM_{2.5}$ and PM_{10} and therefore we needed to use different subsets of the hospitalizations data when considering different exposure lags for $PM_{10-2.5}$. However, since our hospitalizations dataset was very large, it is unlikely that the differences observed between the exposure lags were driven by the lack of daily $PM_{10-2.5}$ concentrations.

Because we were unable to obtain daily concentrations of $PM_{10-2.5}$ for every county in our study, we were unable to examine multi-day effects of $PM_{10-2.5}$ using distributed lag models (Schwartz 2000; Welty and Zeger 2005) or an exposure averaged over multiple days. Previous studies have found larger associations between $PM_{10-2.5}$ and hospitalizations using the average $PM_{10-2.5}$ concentration over 0 to 2 or 0 to 3 days preceding hospitalization (Qiu et al. 2013; Chen et al. 2004; Bell et al. 2008). If the effect of $PM_{10-2.5}$ on hospitalizations extends for multiple days, our study may underestimate associations by using single day exposure lags for $PM_{10-2.5}$.

To decrease the impact of outlying monitor values in our analysis, we used a 10% trimmed mean to estimate the concentration of $PM_{10-2.5}$ within a county for days when multiple measurements of $PM_{10-2.5}$ could be estimated. However, $PM_{10-2.5}$ is a spatially heterogeneous pollutant (EPA 2009) and this approach may not sufficiently adjust for spatial misalignment error introduced by observing $PM_{10-2.5}$ at ambient monitors. A previous study of $PM_{10-2.5}$ did not find that estimated health effects differed substantially between using a 10% trimmed mean and using a more complex measurement error model for $PM_{10-2.5}$ (Chang et al. 2011).

Most studies of the associations between $PM_{10-2.5}$ and hospitalizations have been conducted outside the U.S. (Brunekreef and Forsberg 2005). One source of $PM_{10-2.5}$ outside the U.S. is dust storms (Bell et al. 2008; Karanasiou et al. 2012; De Longueville et al. 2013), which are not as common in the eastern U.S. and may lead to differences in the chemical composition of $PM_{10-2.5}$ between the U.S. and other countries. Our study results may not be comparable to studies outside the U.S. because of other characteristics such as differences in personal exposure, differences in the health care systems, or differences in the health profile of the population under consideration. The study we have conducted here is limited to U.S. adults over 65 enrolled in Medicare and may not be generalizable to other, younger populations or populations outside the U.S.

Conclusion

In a national-level study of the U.S. Medicare population aged 65 years and above, we found that short-term exposure to PM10-2.5 was associated with increased same-day cardiovascular hospitalizations. This association between PM10-2.5 and cardiovascular hospitalizations remained statistically significant after adjusting for same-day concentrations of PM2.5. While previous studies have been inconsistent, in this study, using the longest time frame yet for examining the short-term health effects of PM10-2.5, we provided statistically significant evidence that short-term increases in the coarse fraction of PM are harmful to human health. Our results indicate that a national monitoring network for PM10-2.5 may be necessary to track associations between PM10-2.5 and adverse health outcomes.

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Table 1. Daily hospital admission rates per 100,000 [median (25^{th} – 75^{th} percentiles)] for the period 1999 to 2010 for both the individual and the overall cardiovascular and respiratory health outcomes.

Outcome	**All Counties**	**Western**	**Eastern**
Cardiovascular Disease	1.85 (1.61 – 2.10)	1.43 (1.24 – 1.66)	1.99 (1.73 – 2.25)
Cerebrovascular Disease	0.41 (0.37 – 0.45)	0.34 (0.29 – 0.39)	0.43 (0.39 – 0.48)
Heart Failure	0.52 (0.45 – 0.59)	0.37 (0.31 – 0.43)	0.57 (0.50 – 0.65)
Heart Rhythm Disturbances	0.34 (0.27 – 0.36)	0.26 (0.22 – 0.29)	0.36 (0.29 – 0.39)
Ischemic Heart Disease	0.52 (0.40 – 0.63)	0.41 (0.32 – 0.52)	0.55 (0.43 – 0.67)
Peripheral Vascular Disease	0.08 (0.05 – 0.09)	0.05 (0.04 – 0.07)	0.08 (0.05 – 0.10)
Respiratory Disease	0.67 (0.57 – 0.82)	0.57 (0.46 – 0.73)	0.71 (0.61 – 0.86)
COPD	0.23 (0.20 – 0.28)	0.17 (0.14 – 0.22)	0.25 (0.22 – 0.30)
Respiratory Tract Infections	0.44 (0.37 – 0.55)	0.40 (0.32 – 0.52)	0.46 (0.39 – 0.57)

Table 2. Levels of coarse particulate matter ($PM_{10-2.5}$), fine particulate matter ($PM_{2.5}$), temperature and dew-point temperature for the period 1999 to 2010.

Exposure	**Median (25th – 75th Percentile)**
$PM_{10-2.5}$ (µg/m^3)	
All Counties	12.78 (9.94 – 15.84)
Western Counties	17.38 (13.07 – 21.99)
Eastern Counties	9.77 (6.73 – 12.90)
$PM_{2.5}$ (µg/m^3)	
All Counties	12.06 (10.12 – 14.22)
Western Counties	10.30 (8.24 – 13.49)
Eastern Counties	12.17 (9.84 – 14.88)
Temperature (^{o}F)	
All Counties	61.35 (48.56 – 73.76)
Western Counties	59.21 (49.61 – 70.87)
Eastern Counties	62.03 (48.45 – 74.09)
Dew-point Temperature (^{o}F)	
All Counties	47.31 (36.48 – 59.15)
Western Counties	40.54 (35.06 – 47.49)
Eastern Counties	49.98 (37.25 – 63.11)

Figure Legends

Figure 1. The location of each of the 110 U.S. counties and their median $PM_{10\text{-}2.5}$ levels over all days for which data were available.

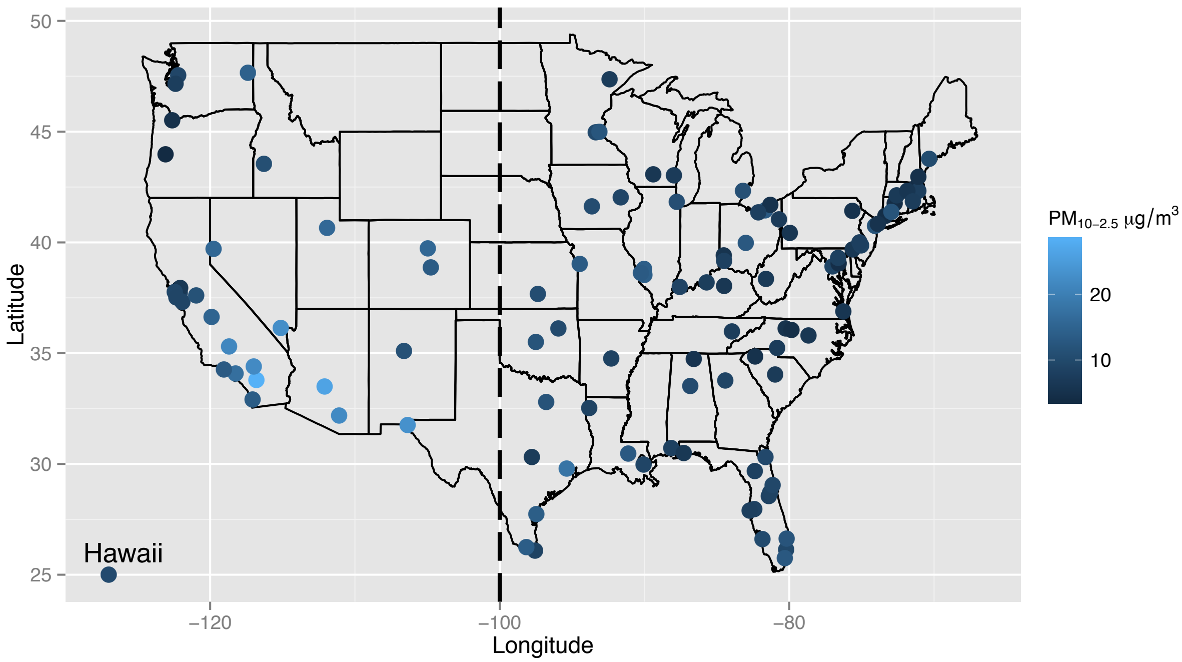
Figure 2. Estimated national level associations (•) and 95% posterior intervals (-) between cardiovascular and respiratory disease admissions and a 10 $\mu g/m^3$ increase in $PM_{10\text{-}2.5}$.

Figure 3. Estimated regional level associations (•) and 95% posterior intervals (-) between cardiovascular and respiratory disease admissions and a 10 $\mu g/m^3$ increase in $PM_{10\text{-}2.5}$.

Figure 4. Estimated national level associations (•) and 95% posterior intervals (-) between cause-specific disease (CVD: cerebrovascular disease; HF: heart failure; HRD: heart rhythm disturbances; IHD: ischemic heart disease; PVD: peripheral vascular disease; COPD: chronic obstructive pulmonary disease; RTI: respiratory tract infection) and a 10 $\mu g/m^3$ increase in $PM_{10\text{-}2.5}$.

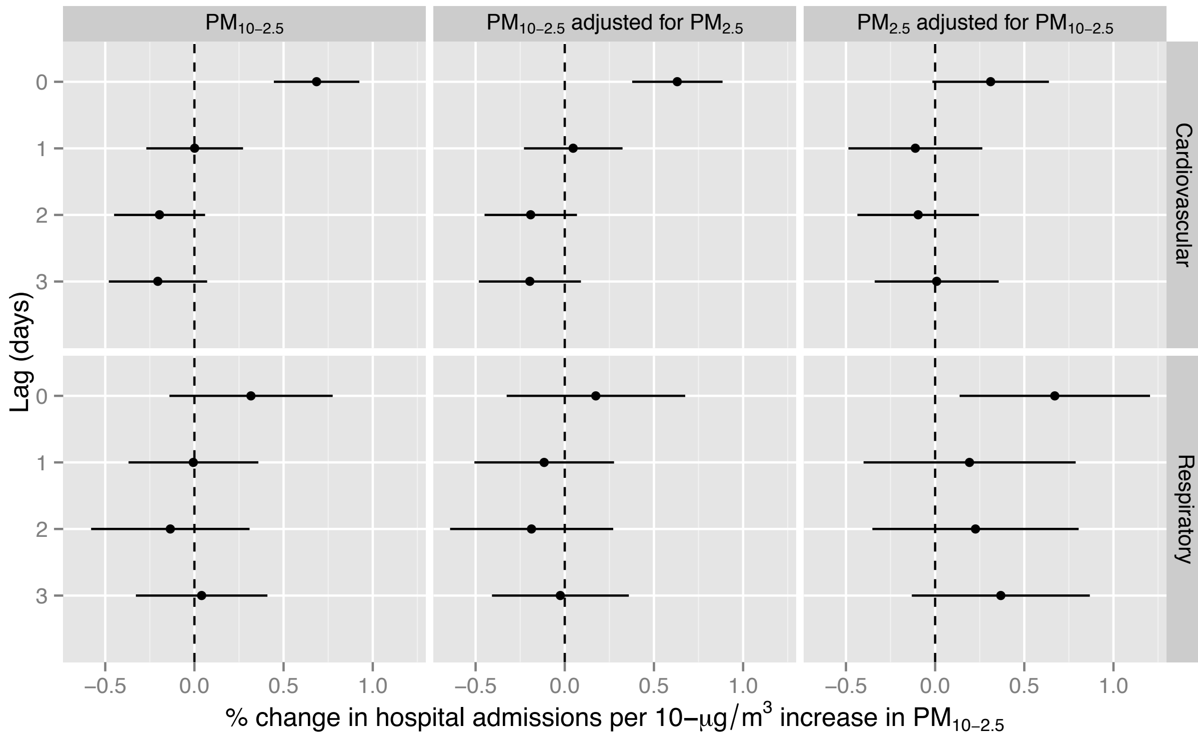
Figure 5. Estimated same day national level associations (•) and 95% posterior intervals (-) between cardiovascular and respiratory disease admissions and a 10 $\mu g/m^3$ increase in $PM_{10\text{-}2.5}$ under varying degrees of freedom for the smooth functions of time, temperature and dew-point temperature. The estimate and posterior interval highlighted in red represent the degrees of freedom used in the final model.

Figure 1.



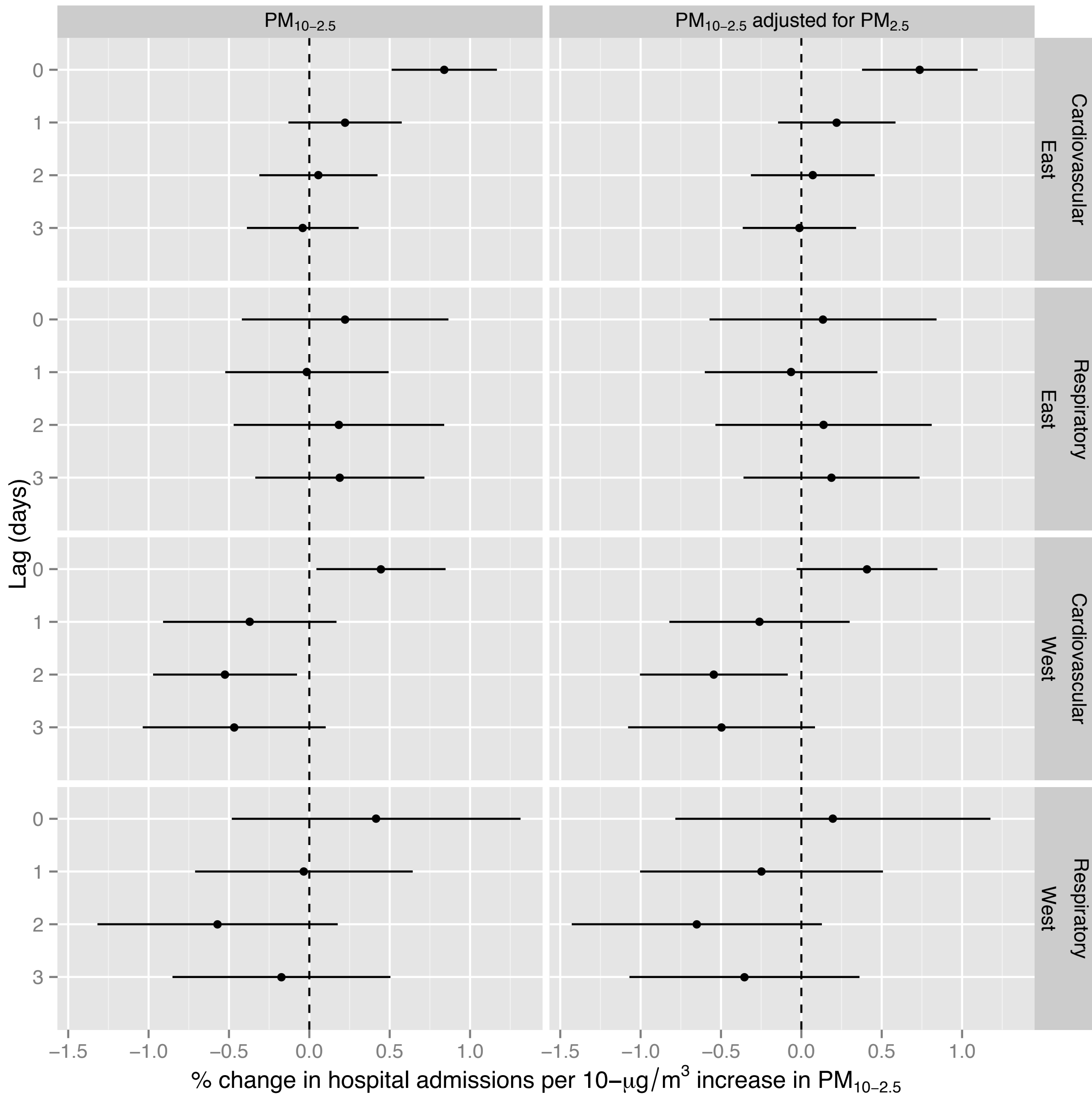
50
45
40
35
30
25
Latitude
Hawaii
−120
−100
−80
Longitude
$PM_{10-2.5}$ µg/m^3
20
10

Figure 2.



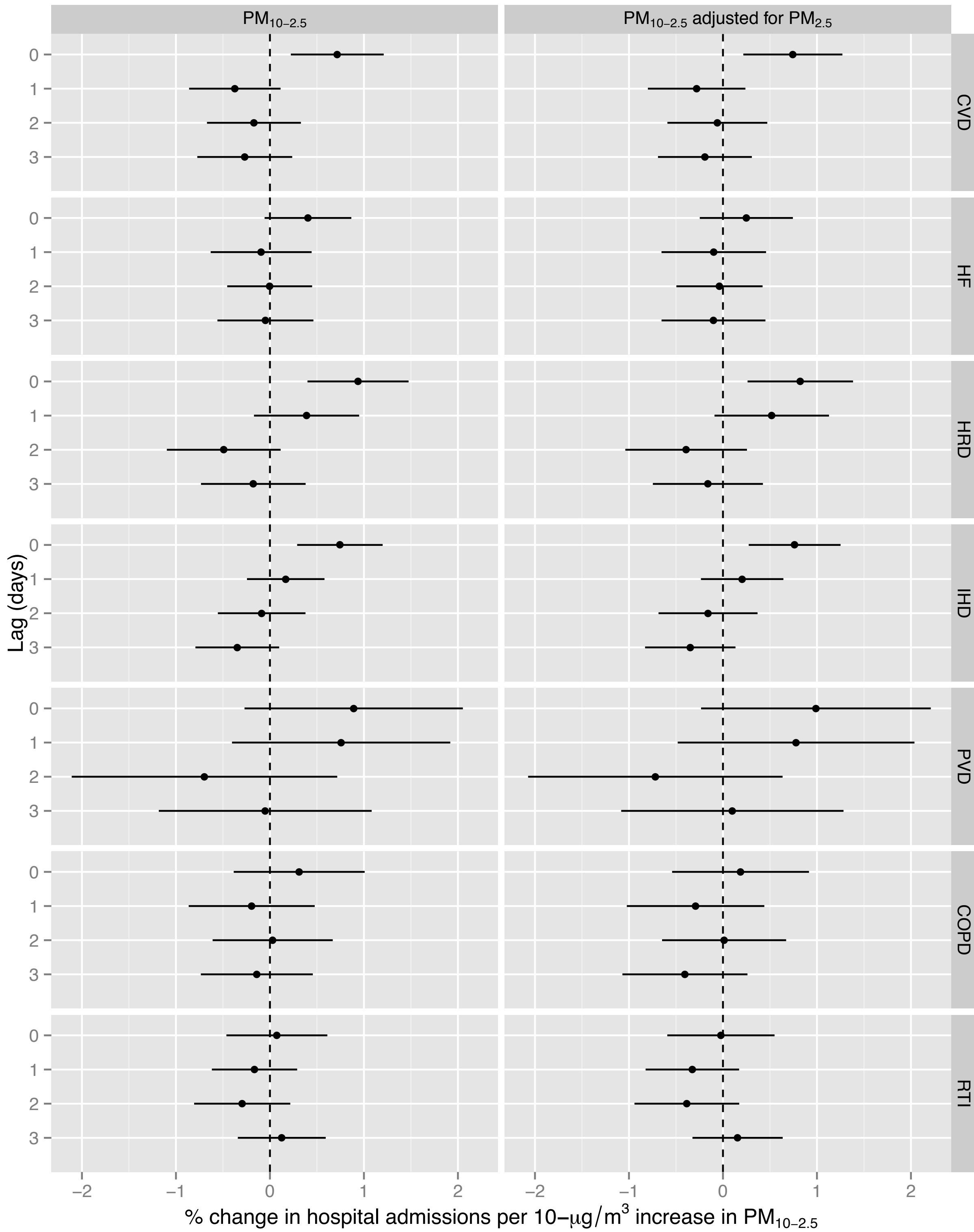
PM10−2.5
PM10−2.5 adjusted for PM2.5
PM2.5 adjusted for PM10−2.5
Cardiovascular
Respiratory
Lag (days)
0
1
2
3
−0.5
0.0
0.5
1.0
% change in hospital admissions per 10−μg/m3 increase in PM10−2.5

Figure 3.



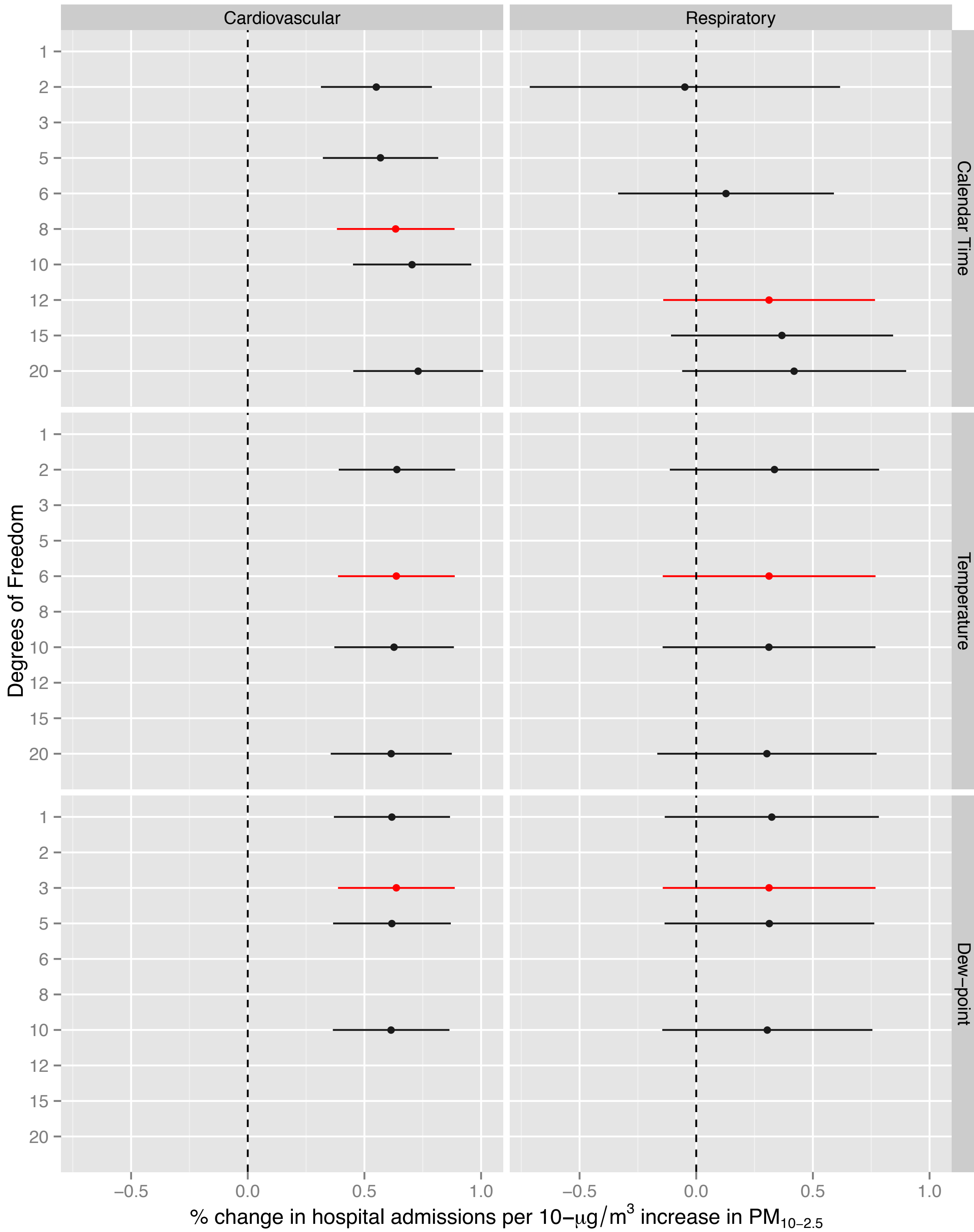
PM10−2.5
PM10−2.5 adjusted for PM2.5
Cardiovascular East
Respiratory East
Cardiovascular West
Respiratory West
Lag (days)
0
1
2
3
−1.5
−1.0
−0.5
0.0
0.5
1.0
% change in hospital admissions per 10−μg/m3 increase in PM10−2.5

Figure 4.



$PM_{10-2.5}$
$PM_{10-2.5}$ adjusted for $PM_{2.5}$
CVD
HF
HRD
IHD
PVD
COPD
RTI
Lag (days)
0
1
2
3
−2
−1
0
1
2
% change in hospital admissions per 10−$\mu g/m^3$ increase in $PM_{10-2.5}$

Figure 5.



Cardiovascular
Respiratory
Calendar Time
Temperature
Dew−point
Degrees of Freedom
1
2
3
5
6
8
10
12
15
20
−0.5
0.0
0.5
1.0
% change in hospital admissions per 10−μg/m3 increase in PM10−2.5